POST-STALL TESTING OF AIRCRAFT WITH A WIND TUNNEL CAPTIVE SYSTEM

J. R. Milillo

ARO, Inc.

November 1972

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

POST-STALL TESTING OF AIRCRAFT WITH A
WIND TUNNEL CAPTIVE SYSTEM

J. R. Milillo
ARO, Inc.

FOREWORD

This study was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 60285F. The results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the AEDC, under Contract F40600-73-C-0004. The work was performed from February through June 30, 1972, under ARO Project No. PW5284, and the manuscript was submitted for publication on July 24, 1972.

This technical report has been reviewed and is approved.

MAURICE A. CLERMONT
Captain, CF
Research and Development
   Division
Directorate of Technology

ROBERT O. DIETZ
Acting Director
Directorate of Technology

ABSTRACT

High-speed aircraft may have unsatisfactory stall characteristics and the aircraft may be lost because of the uncontrolled flight gyrations encountered in attempting to maneuver in the stalled flight regime. Results are presented of a study to determine the feasibility of using a captive technique in a wind tunnel to study aircraft post-stall characteristics and to define boundaries for maintaining controlled flight of the aircraft. The technique appears feasible but needs to be developed by conducting pilot tests in an existing facility.

CONTENTS

APPENDIX
ILLUSTRATIONS

Figure

SECTION I
INTRODUCTION

High-speed aircraft of current designs can have unsatisfactory stall characteristics. The first indication the pilot may receive may be a sudden, high acceleration in a vertical or lateral direction. Such flight characteristics are very unsatisfactory and may place such a high demand on the pilot's attention that he cannot fulfill the basic mission. If insufficient attention is given to aircraft handling, he may not have enough time for recovery from the erratic flight attitudes. For example, in combat maneuvers the aircraft may be lost because of the sudden, uncontrolled flight gyrations encountered in attempting to maneuver in the stalled flight regime.

To alleviate the extreme pilot attention required as flight progresses toward the stalled regime, a "stall inhibitor" has been proposed as an addition to the flight control system of the aircraft. Such a system will greatly improve the safety of operation of high performance aircraft during combat maneuvers and allow the pilot to take best advantage of his equipment without concern for loss of control of the aircraft. One of the primary design requirements of such a control system is the definition of the flight conditions at which loss of control may occur. That is, for each aircraft a flight boundary must be defined in terms of Mach number, altitude, angle of attack, and angle of sideslip.

The flight boundaries may be obtained from actual flight tests, free-flight model tests or wind tunnel tests. The wind tunnel tests could be the normal type of aerodynamic tests during which a complete detailed grid of variables would be examined and then calculations performed to determine the resulting flight motion. Another wind tunnel test technique that could be valuable for such testing is the "captive trajectory" testing technique. Such a technique is presently being used to define the trajectory of stores when released from an aircraft. The store is mounted on an internal balance which is in a closed loop with an electronic computer and the store support system. During such a captive flight, the forces on the model are measured and, knowing the model mass properties, the model accelerations are computed and the complete model trajectory determined.

The results are presented herein of a preliminary study to determine the feasibility of using a Captive Trajectory System (CTS) to study aircraft post-stall characteristics and to define the aircraft flight boundaries for satisfactory controlled flight.

SECTION II
DESCRIPTION OF AIRCRAFT MOTION

In the classical sense, "stall" has been defined as that point when the lift of an airfoil section has dropped off. That is, as the airfoil angle of attack is increased the lift also increases; at some angle of attack sufficient separation occurs on the surface of the airfoil, the lift drops off, and the airfoil is said to have stalled. Such a definition is unsatisfactory when considering the characteristics of a complete aircraft. Many current aircraft designs possess high angle-of-attack lift and stability characteristics that preclude a reliable and recognizable stall over a wide range of entry conditions. If stall is not clearly

evident to the pilot in terms of natural aircraft behavior at high angles of attack, then stall must be defined arbitrarily in other terms so that a safe operational limit is established.

In the current practice of flight testing, stall or "stall angle" is defined as the angle of attack for maximum usable lift at a given flight condition. The phrase "maximum usable lift" indicates there may be a greater lift potential beyond stall but that it is not usable for some reasons. Attempts to use the lift beyond this angle of attack will invite loss of control. On this basis, the following terms have been established and are in current usage:

Stall -   Angle of attack for maximum usable lift

Departure -   Departure from controlled flight is defined as the
                                 first aircraft motion immediately following loss of
                                 control by the pilot. Departure is the beginning
                                 of the post-stall gyration

Post-Stall Gyration -   The uncontrollable motion about one or more
                                 axes, following departure

Incipient Spin -   The initial stage of a spin in which an insufficient
                                 balance between aerodynamic and inertial
                                 moments exists prior to a fully developed spin

Developed Spin -   That motion when there is sufficient balance
                                 between aerodynamic and inertial moments to
                                 allow identification of a spin mode

It can be seen from the above definitions that the events generally follow the order of presentation. The four terms have been defined to assist the visualization of an aircraft flight as it progresses from the normal flight condition to the condition of a developed spin. It should be noted that for many aircraft, a developed spin may not occur for certain control and weight configurations. Spin characteristics of aircraft have been the subject of many studies, but it has been only recently that emphasis has been placed on the flight regime between so called aircraft stall and spin. Reviews of the high angle-of-attack aerodynamic phenomena and flight characteristics are presented in Refs. 1, 2, and 3.

Since one of the basic objectives of the stall program is to develop a control system to avoid the uncontrollable flight regime, the boundaries that must be established for each aircraft can be defined as the departure boundaries. Two examples of aircraft behavior in the post-stall regime are presented in Fig. 1 (Appendix) and represent flight characteristics of the F-4 and T-38 aircraft. The data in Fig. 1a indicate the aircraft was in a shallow left-hand diving turn when the aircraft rolled 180 deg, returned, and oscillated in pitch. The time between 4 and 18 sec can be identified as a post-stall gyration. In Fig. 1b the aircraft was in straight and level flight, the pilot moved the control column forward and rearward, the aircraft angle of attack increased and departure occurred. The post-stall gyration occurred between about 6 to 12 sec in time.

2

Flight data also indicate that for certain flight conditions the post-stall gyration is a function of control surface deflection rate. One objective of post-stall testing would be to determine when the motion could be considered to be a fixed control deflection phenomenon or when the motion is a function of the control deflection rate.

It should be noted that although departure is defined as the beginning of the post-stall gyration or when the pilot first loses control of the aircraft, criteria have yet to be established to define that point in terms of aerodynamic characteristics. Until such criteria are established, it becomes necessary to study the post-stall gyration as a flight regime and to determine the effects of various aircraft parameters and flight conditions on the aircraft motion.

Aircraft post-stall characteristics have been studied experimentally during flight tests, but of necessity such studies are limited because of the constraints of such testing. Calculations of the motion, as reported in Ref. 4, are difficult to accomplish because of the nonlinearity of the aerodynamic coefficients as functions of angle of attack and sideslip. Such nonlinearities therefore necessitate extensive experimental data as inputs to the computer programs to adequately define the aerodynamic forces on the aircraft.

SECTION III
DISCUSSION

3.1 CAPTIVE TRAJECTORY SYSTEM

A system similar to a CTS can permit the study of the aircraft post-stall gyration in a wind tunnel. The CTS was conceived to determine the trajectory of a store when released from an aircraft. For such separation testing, two separate and independent support systems are used to support the models. An isometric drawing of a store separation installation in the Aerodynamic Wind Tunnel (4T) Propulsion Wind Tunnel Facility (PWT), is shown in Fig. 2 and a photograph of a typical installation is shown in Fig. 3. The parent model is inverted and supported by an offset sting attached to the main pitch sector. The store model is supported by the CTS which extends down from the top wall and provides movement (six degrees of freedom) independent of the parent model. Also shown in Fig. 2 is a diagram of the computer control loop used during captive trajectory testing. The analog system and the digital computer work as an integrated unit and, along with the required input information, control the store movement during a trajectory.

The wind tunnel operating conditions, store internal balance forces and moments, and the CTS rig positions are input to the digital computer program. In applying the data to the calculations for the full-scale trajectory, the measured forces and moments are reduced to coefficient form and then applied with the proper full-scale store dimensions and flight dynamic pressure. The digital computer is programmed to solve the six-degree-of-freedom equations to calculate the angular and linear displacements of the store relative to the parent aircraft. In general, the program involves using the previous two successive measured values of each static aerodynamic coefficient to predict the magnitude of the coefficients over the next time interval of the trajectory. These predicted

values are used to calculate the new position and attitude of the store at the end of the time interval. The CTS is then commanded to move the store model to the new position and the aerodynamic loads measured. If the new measurements agree with the predicted values, the process is continued over another time interval of the same magnitude. If the measured and predicted values do not agree within the desired precision, the calculation is repeated over a time interval one-half the previous value. This entire process is repeated until a complete trajectory has been obtained. A complete description of the CTS and its operation is presented in Ref. 5.

3.2 STALL/POST-STALL TESTING WITH A CAPTIVE SYSTEM

The captive system represents a calculation technique wherein the basic aerodynamic inputs to the program are measured only at the specific test conditions and input during the test rather than chosen from a table of values. Therefore, the very obvious advantage of the captive technique is the elimination of the requirement for extensive measurements of the aerodynamic characteristics for each desired configuration. For example, if the stall characteristics were desired for various external store carriage configurations of the aircraft, the complete aerodynamic characteristics would have to be obtained for each configuration. The elimination of the extensive data requirements also permits the rapid evaluation of the sensitivity of the aircraft motion to such parameters as center-of-gravity location, aircraft inertia, aerodynamic damping, and engine thrust.

A second advantage of the captive technique is the possiblity of evaluating flight control systems that have been designed to avoid aircraft flight near departure. The characteristics of such control systems can be modeled and used as another subroutine to the computer program during the captive test. The test would be conducted with and without the flight control system simulation to determine its effectiveness.

The use of a captive technique to study the motion of an aircraft in the stall/post-stall regime will not require a six-degree-of-freedom movement as in the case for store testing. For post-stall tests in the wind tunnel, the attitude of the aircraft has to be established only as a pitch and roll motion with the added requirement that the model remain near the center of the test section. However, the other quantities concerned with linear motion would be calculated and tabulated as part of the complete data reduction procedure.

A number of parameters have been identified that must be given specific consideration if a captive technique is to be used for testing to study post-stall gyration or departure boundaries.

3.2.1 Engine Thrust

The simulation of engine thrust is important because of the possibility of extreme thrust variations during the departure mode. For a single engine aircraft, the thrust may be reduced to zero because of an engine flameout, and for a twin engine aircraft, large moments may be caused by a single engine-out condition. Because of model scale (to be discussed later), the use of mechanical or pneumatic devices to simulate engine

installation is highly improbable. Therefore, the engine thrust must be simulated mathematically. The mathematical techniques for variation of thrust during a given test are bounded by two methods. The simplest technique would assume that the thrust remained constant up to a given point (attitude) and then diminished to zero at some predetermined point. The other extreme represents the most exact simulation possible and would utilize the math models that are presently being developed by engine manufacturers. Such models describe the complete engine operating conditions and in some cases define the characteristics of the entire inlet-engine installation. During the test, the attitude of the aircraft, test conditions, and possibly certain inlet pressure measurements would be inputs to the engine math model which in turn could be considered as a subroutine of the computer program that calculates the aircraft motion. Since the engine operating conditions would be known, such an engine math model would also allow for better simulation of the engine gyroscopic forces on the aircraft motion. Such use of the engine math-models requires further study but does not appear impossible at this time. As stated previously, the captive technique would permit the evaluation of the sensitivity of the aircraft motion to any thrust variation desired.

3.2.2 Mach Number

The variation of Mach number at departure or during the post-stall gyration could be significant and should be simulated during the wind tunnel test. For some aircraft configurations, the Mach number just at, and after, departure may be essentially constant and therefore represents no difficulties for the captive test. For those configurations which have a significant variation in Mach number during the post-stall gyration (as shown in Fig. 1), it would be highly advantageous for the wind tunnel Mach number to be automatically controlled in response to the captive system computer output. At present, such an automatic control system is not feasible because of the many variables that establish the wind tunnel stream Mach number. However, the captive test could be conducted on a point-to-point basis. That is, for each point in time the motion is calculated, the Mach number is also calculated and displayed. The tunnel operator then sets the new required Mach number for the next point in the time sequence and the test is continued.

3.2.3 Angular Motion

The extreme angular motions. especially in pitch, may present certain difficulties for the captive technique. The limits of two current system designs are 45 deg for pitch and yaw angle and 360 deg for roll angle. The roll angle limitation should be adequate to establish the departure point. Considering the available flight data, and as indicated in Fig. 1, it appears that the 45-deg limitation for yaw angle should be sufficient although there may be some aircraft configurations which require a larger value. The limit of 45 deg in pitch appears to be unsatisfactory. For some aircraft the departure point may occur at a relatively large angle of attack, and since data would be required above the departure point, the 45-deg limitation would not be satisfactory. It may be possible to conduct a given test up to the angle limit then interrupt the test and change the support for continued testing beyond the 45-deg setting. However, since the aircraft motion can be oscillatory such a procedure might not be usable. Therefore, it appears at this time that the pitch angle capability of the captive system should approach 90 deg. It should be

noted that the aircraft pitch angle may be small during flight, but the angle of attack can be very large because of the "pitch and plunge" motion of the aircraft. Since the relative wind in a wind tunnel is fixed (generally in the horizontal plane), the support system must satisfy the angle-of-attack requirement rather than the pitch angle requirement. The same requirement exists for the yaw angle; however the excursion rate generally is not as large as for the pitch motion.

3.3 MODEL SIZE

The aircraft departure and post-stall gyration are essentially high angle-of-attack phenomena. The flow about the aircraft is characterized by unsymmetrical regions of flow separation and therefore sensitive to Reynolds number. Such a consideration leads to the requirement for a large model size and/or a high density wind tunnel to achieve the highest possible Reynolds number. In addition, since the aircraft angle of attack approaches 90 deg, the tunnel blockage caused by the model becomes an important consideration. At $a = 90$ deg, the tunnel blockage should not exceed one percent. That is, the planform area of the model should not exceed one percent of the wind tunnel cross-sectional area to avoid wind tunnel wall interference effects on the aerodynamic characteristics of the model. A third important consideration is the requirement that the model has remotely controlled flight control surfaces, since as previously stated the post-stall gyration can be a function of control surface deflection rate.

If consideration is also given to model cost and availability, the conclusion is reached that 0.05-scale models approach an optimum size for post-stall testing. Such a size is presently used in small wind tunnels (PWT-4T, for example) to determine aircraft performance and represents the smallest size which can provide enough space for an internal balance and a drive system for airfoil control surfaces. In conjunction with the PWT-16T, which is the largest variable density wind tunnel available, it can be seen below that the tunnel blockage with 0.05-scale models of two aircraft of current interest is less than the limit of one percent.

Aircraft	Planform Area at $a = 90$ deg, ft^2	Percent Blockage PWT-16T
A-7	1.442	0.56
F-4	1.898	0.74

3.4 MODEL SUPPORT SYSTEM

The two basic forces that guide the design of the model support system are the model normal force and axial force and, of these, the normal force is the most important. The normal force and axial force for a model of the F-8 aircraft are presented in Fig. 4. The data are based on the results presented in Ref. 6 and were computed for a wing reference area of 1 sq ft which approximates a 0.05-scale model. The forces in Fig. 4. are presented for two values of tunnel dynamic pressure, q, which represent the nominal minimum and maximum values for PWT-16T. To obtain the maximum Reynolds number, it can be seen that the model support system would need a capability of approximately

1600-lb normal force and 60 lb of axial force at α = 90 deg. The axial force does not present any problems; however, the normal-force requirement exceeds the capacity of existing support systems. Therefore, design studies will be required to establish a support system design to meet the high loads associated with post-stall testing at a high Reynolds number.

SECTION V
CONCLUDING REMARKS

Captive testing to determine aircraft post-stall characteristics appears to be feasible. The model size requirements are not excessive, and the support system requirements do not appear to be impossible although a design study is required. It is recommended that an effort be undertaken to develop the technique utilizing pilot tests in the PWT-4T with the Captive Trajectory System. Further study of flight test data is also required to establish the parameters that must be varied in the wind tunnel tests and to establish the new requirements for the CTS computer program for post-stall testing.

REFERENCES

1. Hancock, G. J. "Problems of Aircraft Behavior at High Angles of Attack." AGARDograph 136, April 1969.

2. Thomas, H. H. B. M. "On Problems of Flight Over an Extended Angle-of-Attack Range." RAE Technical Report 71013, January 1971.

3. Symposium Stall/Post Stall/Spin, ASD and AFFDL, December 1971.

4. Scher, S. H. "Post-Stall Gyrations and Their Study on a Digital Computer." AGARD Report 359, April 1961.

5. Christopher, J. P. and Carleton, W. E. "Captive Trajectory Store-Separation System of the AEDC-PWT 4-Foot Transonic Tunnel." AEDC-TR-68-200 (AD839743), September 1968.

6. Grantham, W. D. and Grafton, S. B. "Effects of Aircraft Relative Density on Spin and Recovery Characteristics of Some Current Configurations." NASA TN D-2243, March 1965.

APPENDIX
ILLUSTRATIONS

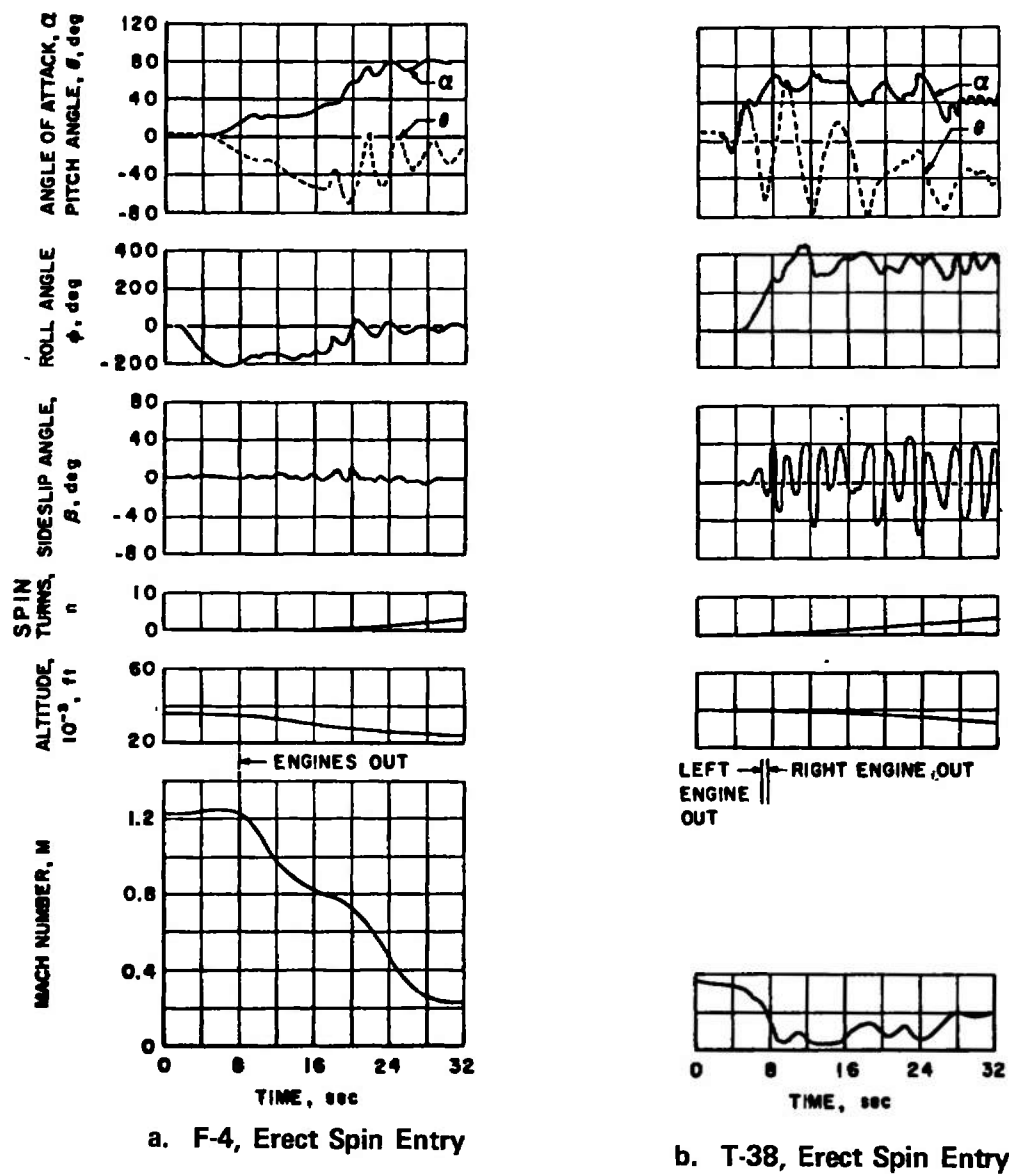a. F-4, Erect Spin Entry

b. T-38, Erect Spin Entry
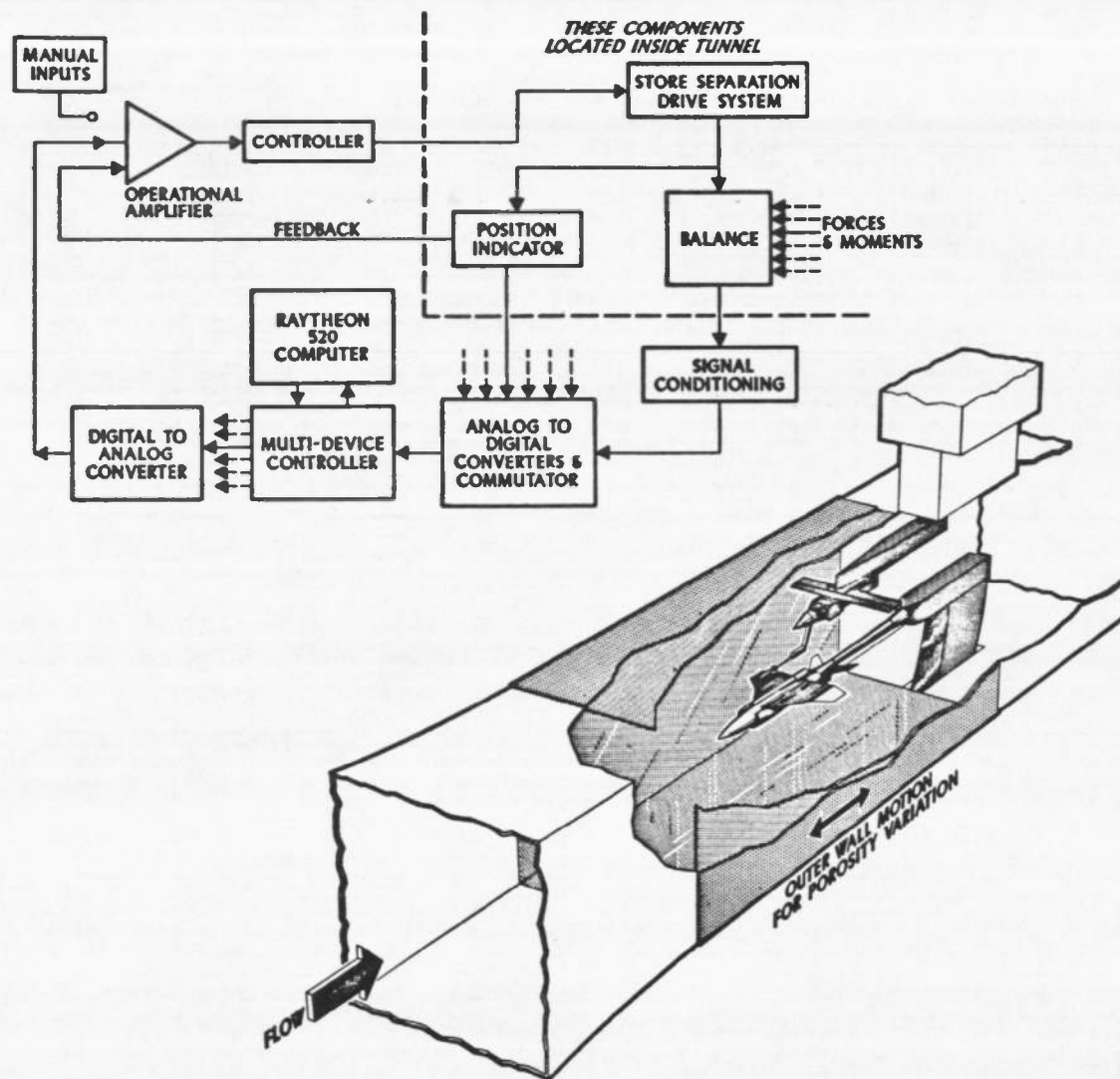
Fig. 1 Aircraft Motion in the Post-Stall Regime

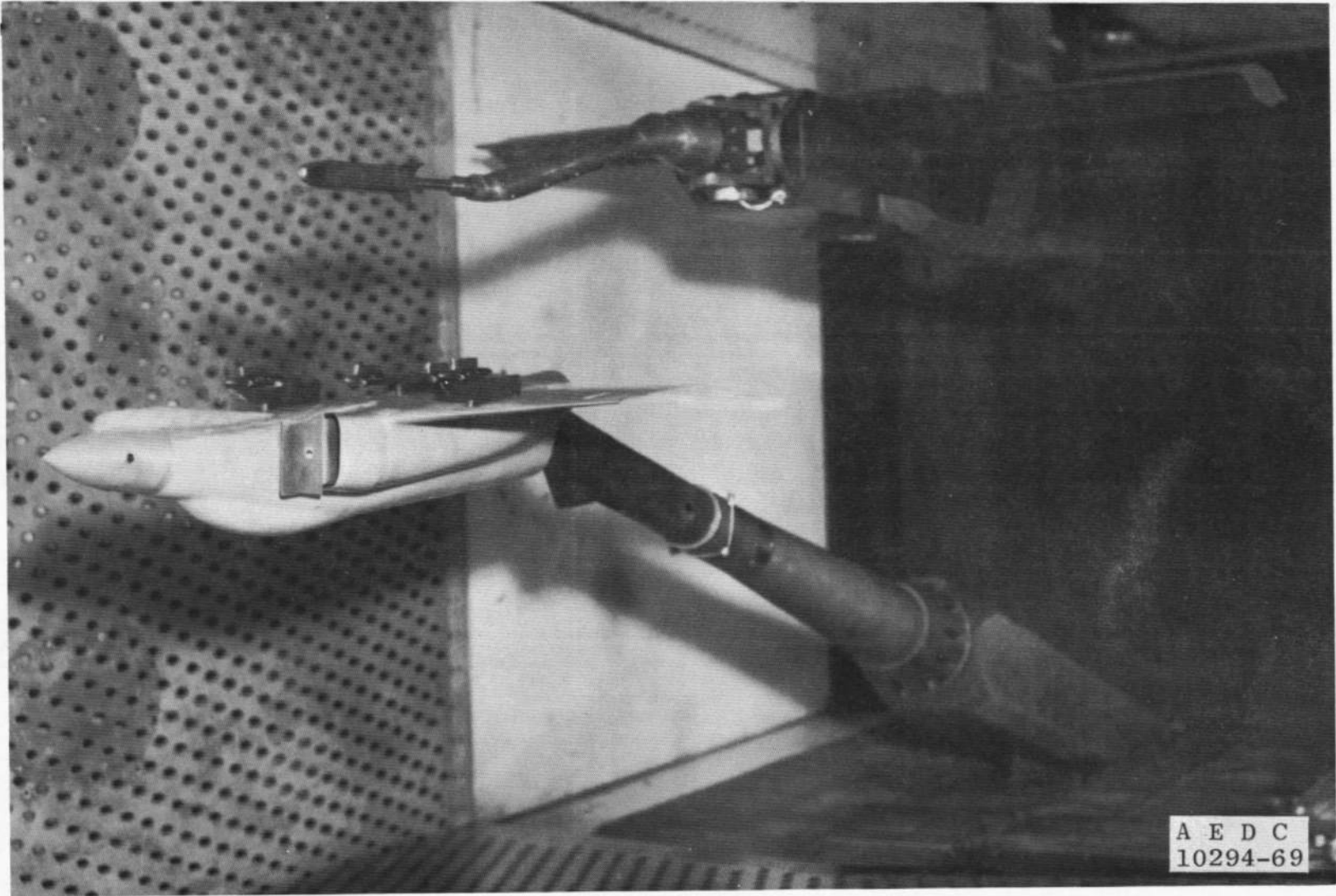Fig. 2 Store Separation Installation and Block Diagram of the Computer Control Loop

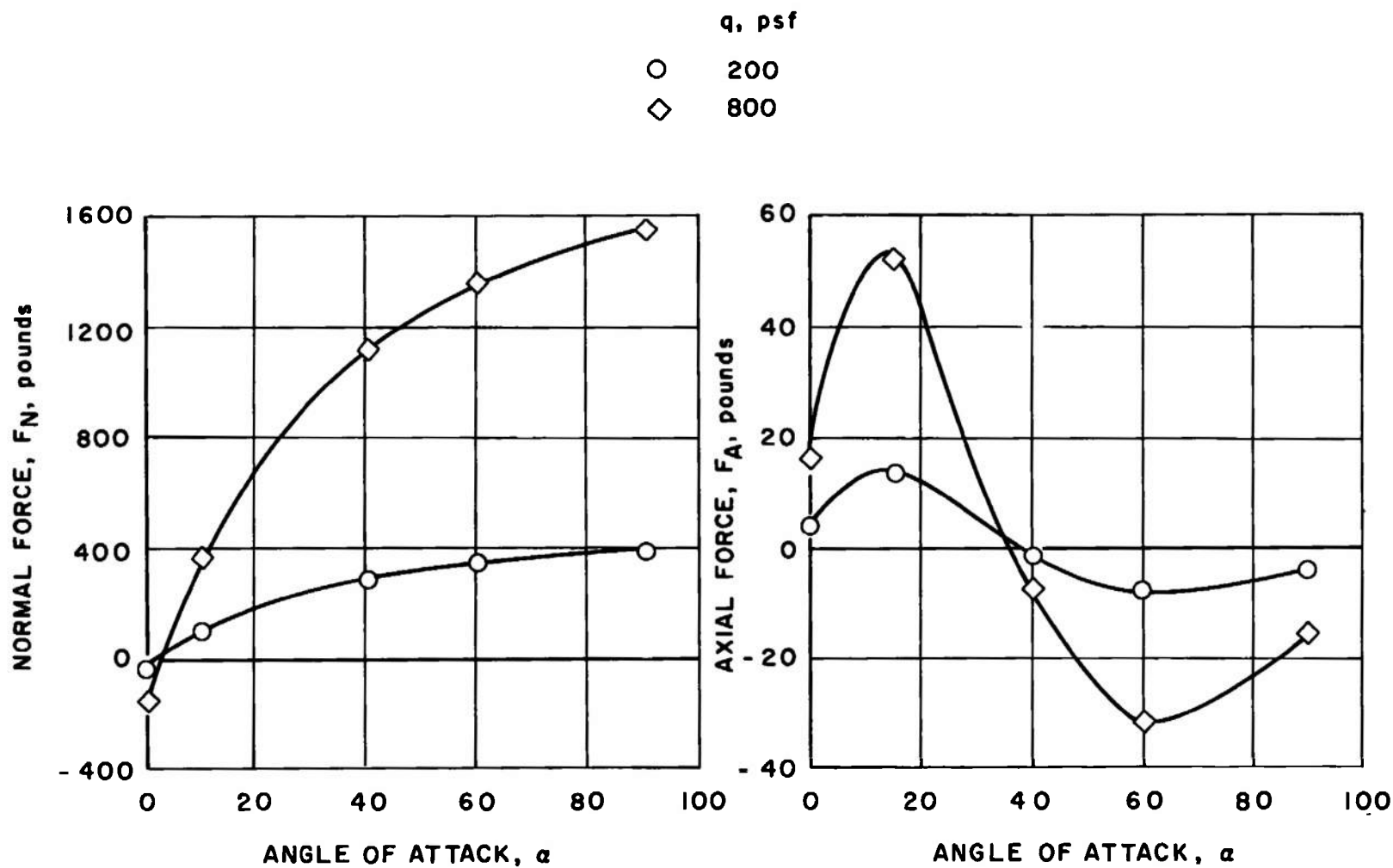Fig. 3 Tunnel Installation for a Captive Trajectory System Test

q, psf

○   200

◇   800

Fig. 4 F-8 Aircraft Model Forces, S_w = 1.0 ft^2

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Arnold Engineering Development Center	**UNCLASSIFIED**
Arnold Air Force Station, Tennessee 37389	2b. GROUP N/A

3 REPORT TITLE

POST-STALL TESTING OF AIRCRAFT WITH A WIND TUNNEL CAPTIVE SYSTEM

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report – February through June 30, 1972

5 AUTHOR(S) *(First name, middle initial, last name)*

J. R. Milillo, ARO, Inc.

6 REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1972	19	6

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	AEDC-TR-72-126
c. Program Element 60285F	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	ARO-PWT-TR-72-115

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Available in DDC	Arnold Engineering Development Center Air Force Systems Command Arnold Air Force Station, Tenn.37389

13 ABSTRACT

High-speed aircraft may have unsatisfactory stall characteristics and the aircraft may be lost because of the uncontrolled flight gyrations encountered in attempting to maneuver in the stalled flight regime. Results are presented of a study to determine the feasibility of using a captive technique in a wind tunnel to study aircraft post-stall characteristics and to define boundaries for maintaining controlled flight of the aircraft. The technique appears feasible but needs to be developed by conducting pilot tests in an existing facility.

DD FORM 1 NOV 65 **1473**

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
aircraft						
stalling						
test methods						
wind tunnels						

AFSC
Arnold AFS Tenn.